

Test particle acceleration by rotating jet magnetospheres

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Abstract. Centrifugal acceleration of charged test particles at the base of a rotating jet magnetosphere is considered. Based on an analysis of forces we derive the equation for the radial accelerated motion and present an analytical solution. It is shown that for particles moving outwards along rotating magnetic field lines, the energy gain is in particular limited by the breakdown of the bead-on-the-wire approximation which occurs in the vicinity of the light cylinder r_L . The corresponding upper limit for the maximum Lorentz factor γ_{\max} for electrons scales $\propto B^{2/3} r_L^{2/3}$, with B the magnetic field strength at r_L , and is at most of the order of a $10^2 - 10^3$ for the conditions regarded to be typical for BL Lac objects. Such values suggest that this mechanism may provide pre-accelerated seed particles which are required for efficient Fermi-type particle acceleration at larger scales in radio jets.

INTRODUCTION

Rotating magnetospheres are widely believed to be responsible for the relativistic jet phenomenon in active galactic nuclei (AGN) [2,1]. Here we address the question whether centrifugal acceleration of charged test particles at the base of such a jet magnetosphere may possibly produce a seed population of relativistic electrons which is required for efficient particle acceleration. For, in order to explain the origin of the nonthermal emission extending up to TeV energies in some blazars, several acceleration processes have been proposed among which Fermi-type particle acceleration mechanisms (i.e. diffusive shock acceleration [4]) are quite promising. However such kind of mechanisms require a pre-accelerated seed population of electrons with Lorentz factors of the order of 100 [10,8]. It seems therefore quite interesting whether in the case of AGN centrifugal acceleration by rotating jet magnetosphere may potentially fill this gap by providing pre-accelerated seed particles. For an analytical treatment, we consider the following simplified model: motivated by MHD-scenarios for the origin of jets via rotating jet magnetospheres [2,3,5] (see Fig. 1) a projected two-dimensional model topology is applied where the magnetic field is supposed to rotate rigidly with a fraction of the rotational velocity of the black hole [5]. Test particles with rest mass m_e and charge e are assumed to be

injected at time t_0 and position r_0 with velocity v_0 parallel to the rotating field line.

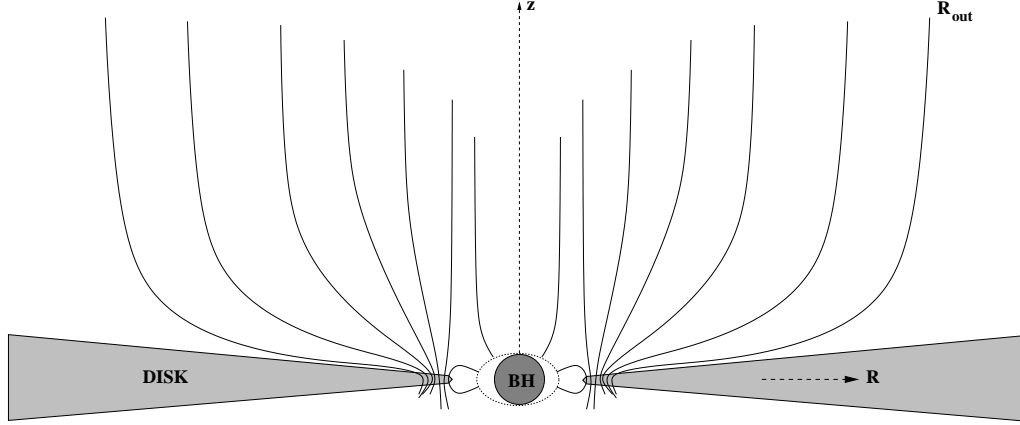


FIGURE 1. Simplified model topology for the asymptotic jet structure around a rotating black hole as expected in MHD scenarios.

MODELLING

Consider the forces acting on a particle in a rotating frame of reference [6,7]: Particles, which are injected at (t_0, r_0) with velocity v_0 along the magnetic field line $B_r(t_0)$ experience a centrifugal force in the radial direction given by

$$\vec{F}_{\text{cf}} = m_e \gamma (\vec{\Omega} \times \vec{r}) \times \vec{\Omega}, \quad (1)$$

where γ denotes the Lorentz factor and $\vec{\Omega} = \Omega \vec{e}_z$ the angular velocity of the field. Additionally, there is also a relativistic Coriolis term in the noninertial frame governed by the equation

$$\vec{F}_{\text{cor}} = m_e \left(2 \gamma \frac{d\vec{r}}{dt} + r \frac{d\gamma}{dt} \right) (\vec{e}_r \times \vec{\Omega}), \quad (2)$$

which acts as a deviation-force in the azimuthal direction. In the inertial rest frame the particle sees the field line bending off from its initial injection position, therefore it experiences a Lorentz force ($c = 1$)

$$\vec{F}_{\text{L}} = e (\vec{v}_{\text{rel}} \times \vec{B}), \quad (3)$$

where v_{rel} is the relative velocity between the particle and the magnetic field line. Due to the Lorentz force a particle tries to gyrate around the field line. Initially, the direction of the Lorentz force is perpendicular to the direction of the Coriolis force, but as a particle gyrates, it changes the direction and eventually becomes

antiparallel to the Coriolis force. Hence, the bead-on-the-wire approximation is valid if the Lorentz force is not balanced by the Coriolis force [7,11]. In this case, the accelerated motion of the particle's guiding center due to the centrifugal force may be written as

$$\gamma \frac{d^2 r}{dt^2} + \frac{dr}{dt} \frac{d\gamma}{dt} = \gamma \Omega^2 r, \quad (4)$$

where $\gamma = (1 - \Omega^2 r^2 - \dot{r}^2)^{-0.5}$. The constrained motion is then given by the azimuthal components of forces

$$\frac{d\gamma}{dt} \leq \frac{1}{r} \left(\frac{B e v_{\text{rel}}}{m_e \Omega} - 2 \gamma \frac{dr}{dt} \right). \quad (5)$$

Generally, the bead-on-the-wire approximation is supposed to break down if F_{cor} exceeds F_L (i.e. when \leq in Eq. 5 becomes $>$).

RESULTS

Using the argument that the Hamiltonian for a bead on a relativistically moving wire $H = \gamma m_e (1 - \Omega^2 r^2)$ is a constant of motion, the equation for the radial accelerated motion could be reduced to a simple form which has been solved analytically yielding [9,11]

$$r(t) = \frac{1}{\Omega} \text{cn}(\lambda_0 - \Omega t), \quad (6)$$

where cn , (sn) is the Jacobian elliptic cosine (sine, respectively), and λ_0 is an elliptic integral of the first kind, i.e.

$$\lambda_0 = \int_0^{\phi_0} \frac{d\theta}{(1 - \tilde{m} \sin^2 \theta)^{1/2}}. \quad (7)$$

with $\tilde{m} = (1 - \Omega^2 r_0^2 - v_0^2)/(1 - \Omega^2 r_0^2)^2$. The Lorentz factor may then be written as

$$\gamma(t) = \frac{1}{\sqrt{\tilde{m}} [\text{sn}(\lambda_0 - \Omega t)]^2}, \quad (8)$$

or, if expressed as a function of the radial co-ordinate, as

$$\gamma(r(t)) = \frac{1}{\sqrt{\tilde{m}} (1 - \Omega^2 r(t)^2)}. \quad (9)$$

Apart from radiation losses (e.g. inverse-Compton losses in the radiation field of the accretion disk, see [11]), the maximum attainable Lorentz factor γ_{max} is in particular limited by the breakdown of the bead-on-the-wire approximation (i.e.

when the particle leaves the field line and thus, acceleration becomes ineffective) in the vicinity of the light cylinder r_L . Using the definition of the Hamiltonian H and Eq. 9 and setting $v_{\text{rel}} = c$, one may derive an upper limit for the maximum Lorentz factor γ_{max} from Eq. 5

$$\gamma_{\text{max}} \simeq \frac{1}{\tilde{m}^{1/6}} \left(\frac{B(r_L) e}{2 m_e c^2} r_L \right)^{2/3}, \quad (10)$$

where $B(r_L)$ denotes the magnetic field strength at the light cylinder and where for clarification c has now been inserted. For typical BL Lac conditions, i.e. a light cylinder radius $r_L \sim 10^{13}$ m, and a field strength $B(r_L) \sim (30-100) \times 10^{-4}$ T, Eq. 10 results in an upper limit on the maximum Lorentz factor $\gamma_{\text{max}} \sim (1 - 2.5) \times 10^3$.

CONCLUSIONS

The results derived in the simple toy-model presented here support flares on accretion disks as providing a seed population of relativistic electrons with Lorentz factors up to $\sim 10^3$ in BL Lac type objects. Such pre-accelerated particles are required for models involving diffusive shock acceleration of e^+/e^- in relativistic jets, cf. [10], [8]. Particle acceleration by rotating jet magnetospheres may thus possibly represent an interesting explanation for the required pre-acceleration.

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